

DIESEL AFTERTREATMENT SYSTEMS

5 Field of Invention

The present invention relates to a system and a method for improving performance of an exhaust gas aftertreatment device and, more particularly, to using an
10 air assist heated reductant delivery system to improve NOx conversion efficiency and reduce fuel penalty.

Background of the Invention

15 Current emission control regulations necessitate the use of catalysts in the exhaust systems of automotive vehicles in order to convert carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NOx) produced during engine operation into harmless
20 exhaust gasses. Vehicles equipped with diesel or lean gasoline engines offer the benefits of increased fuel economy. Such vehicles have to be equipped with lean exhaust aftertreatment devices such as, for example, Active Lean NOx Catalysts (ALNC), which are capable of
25 continuously reducing NOx emissions, even in an oxygen rich environment. In order to maximize NOx reduction in the ALNC, a hydrocarbon-based reductant, such as fuel (HC), has to be added to the exhaust gas entering the device. However, introducing fuel as a reductant
30 reduces overall vehicle fuel economy. Therefore, in order to achieve high levels of NOx conversion in the ALNC while concurrently minimizing the fuel penalty, it is important to optimize usage of injected reductant.

In this regard, it is known that improved NOx

conversion can be achieved by introducing the reductant in vapor rather than liquid form due to better distribution and mixing of the reductant with the exhaust gas entering the NO_x reduction device.

5 One such system is described in US patent 5,771,689, wherein a reductant is introduced into the exhaust gas via an evaporator device that has a hollow body with a heating element protruding into its interior. The evaporator device protrudes into the wall of the exhaust pipe upstream of the catalyst. The reductant is
10 introduced so that it flows through the narrow space between the hollow body and the heating element until it reaches the tip of the heating element from where it enters the exhaust pipe in vapor form and mixes with the
15 exhaust gas entering the catalyst.

 The inventors herein have recognized several disadvantages with this approach. Namely, if delivery of the reductant has been shut off, or reduced, as dictated by the operating conditions, some reductant may remain in
20 the annular space, in contact with the heating element, and may therefore clog up the opening around the heating device by carbonation of the residual fuel. Such carbon build up may lead to a blockage of the passage at the tip by which the vaporized fuel enters the exhaust stream.
25 Further, there is a delay in introducing the reductant into the exhaust gas stream due to the time it takes for the reductant to travel down the length of the heating element. Additionally, durability of the heating element is reduced because its temperature is not controlled and
30 adjusted based on operating conditions, and due to soot contamination. Yet another disadvantage of the prior art approach is that extra power is consumed due to the above-mentioned lack of temperature control.

Summary of the Invention

The present invention teaches a system and a
5 method for introducing evaporated reductant into an
exhaust gas stream entering a lean exhaust gas
aftertreatment device while eliminating the above-
mentioned disadvantages of the prior art approaches.

In accordance with the present invention, a
10 reductant delivery system includes: an evaporator unit
including at least a heating element; a mixing device
having at least one inlet and at least one outlet, said
outlet coupled to said evaporator unit; and a controller
for introducing reductant and air into said mixing device
15 through said inlet, injecting a mixture of said reductant
and said air through said outlet into said evaporator
unit thereby causing evaporation of said reductant and
air mixture.

In another aspect of the present invention, a
20 method for controlling a reductant delivery system having
at least a heating element, the system coupled upstream
of an exhaust system of an internal combustion engine in
a mobile vehicle, includes: injecting air into the
reductant delivery system; injecting a reductant into the
25 reductant delivery system thereby creating a vaporized
mixture; and directing said vaporized mixture into the
exhaust system of the engine.

The present invention provides a number of
advantages. In particular, creating a mixture of
30 reductant and air improves the exhaust gas aftertreatment
device efficiency, due to the enhanced mixing of the
reductant with the bulk exhaust flow and improved
catalytic action relative to the use of liquid phase
reductant. Additionally, mixing reductant with air

breaks up the reductant in small particles, thus resulting in faster evaporation process. Additionally, injecting air into the vaporizer unit prevents lacquering and soot deposits on the surface of the heating element.

5 Further, the inventors have recognized that dynamically controlling the temperature of the heating element to take advantage of the heat supplied by the exhaust gasses prevents overheating, improves the heating element durability and reduces power consumption.

10 Yet another advantage of the present invention is that the heating element temperature can be controlled to ignite the injected reductant and air mixture, and thus produce carbon monoxide (CO), which further improves NOx reduction in the ALNC.

15 It is a further advantage of this invention that CO generation is increased (and thus NOx conversion efficiency increased) by placing an oxidizing catalyst in the path of the reductant and air mixture prior to its mixing with the exhaust gasses.

20 The above advantages and other advantages, objects and features of the present invention will be readily apparent from the following detailed description of the preferred embodiments when taken in connection with the accompanying drawings.

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Brief Description of the Drawings

The objects and advantages described herein will be more fully understood by reading an example of an embodiment in which the invention is used to advantage, referred to herein as the Description of Preferred Embodiment, with reference to the drawings, wherein:

30 Figures 1A and 1B are schematic diagrams of an engine wherein the invention is used to advantage;

Figure 2 is a an example of one embodiment of an emission control system wherein the present invention is used to advantage;

Figures 3A, 3B and 3C are examples of reductant
5 delivery systems in accordance with the present invention;

Figure 4 is a high level flowchart of an exemplary routine for controlling a temperature of the heating element of the reductant delivery system in
10 accordance with the present invention;

Figures 5 and 6 describe an exemplary routine and a modification curve for determining an amount of reductant to be delivered to the exhaust gas aftertreatment device in accordance with the present
15 invention.

Description of Preferred Embodiment(s)

Internal combustion engine 10, comprising a
20 plurality of cylinders, one cylinder of which is shown in Figure 1, is controlled by electronic engine controller 12. Engine 10 includes combustion chamber 30 and cylinder walls 32 with piston 36 positioned therein and connected to crankshaft 40. Combustion chamber 30 is
25 shown communicating with intake manifold 44 and exhaust manifold 48 via respective intake valve 52 and exhaust valve 54. Intake manifold 44 is also shown having fuel injector 80 coupled thereto for delivering liquid fuel in proportion to the pulse width of signal FPW from
30 controller 12. Both fuel quantity, controlled by signal FPW and injection timing are adjustable. Fuel is delivered to fuel injector 80 by a fuel system (not shown) including a fuel tank, fuel pump, and fuel rail (not shown).

Controller 12 is shown in Figure 1 as a conventional microcomputer including: microprocessor unit 102, input/output ports 104, read-only memory 106, random access memory 108, and a conventional data bus.

5 Controller 12 is shown receiving various signals from sensors coupled to engine 10, in addition to those signals previously discussed, including: engine coolant temperature (ECT) from temperature sensor 112 coupled to cooling sleeve 114; a measurement of manifold pressure
10 (MAP) from pressure sensor 116 coupled to intake manifold 44; a measurement (AT) of manifold temperature from temperature sensor 117; an engine speed signal (RPM) from engine speed sensor 118 coupled to crankshaft 40.

An emission control system 20, coupled to an
15 exhaust manifold 48, is described in detail in Figure 2 below.

Referring now to Figure 1B, an alternative embodiment is shown where engine 10 is a direct injection engine with injector 80 located to inject fuel directly
20 into cylinder 30.

Referring now to Figure 2, an example of one embodiment of an emission control system wherein the present invention is used to advantage is described. Emission control system 20 is coupled downstream of an
25 internal combustion engine 10 described with particular reference in Figure 1. Catalyst 14 is an Active Lean NOx Catalyst (ALNC) capable of reducing NOx in an oxygen rich environment. Oxidation catalyst 13 is coupled upstream of the ALNC and may be a precious metal catalyst,
30 preferably one containing platinum. The oxidation catalyst exothermically combusts hydrocarbons (HC) in the incoming exhaust gas from the engine thus supplying heat to rapidly warm up the Active Lean NOx Catalyst (ALNC) 14. Additionally, carbon monoxide (CO) produced as a

result of HC combustion in the oxidation catalyst 13 improves NOx reduction in the ALNC. Particulate filter 15 is coupled downstream of the ALNC and is capable of storing carbon particles from the exhaust.

5 A reductant delivery system 16 is coupled to the exhaust gas manifold between the oxidation catalyst and the ALNC. Alternative embodiments of the reductant delivery system are described later herein with particular reference to Figures 3A - 3C.

10 The diagram of Figure 3A generally represents an example of one embodiment of a reductant delivery system according to the present invention. The system comprises an evaporator unit 21 housing an elongated heating element 22. In this example, the heating element
15 is an electrically heated cylindrically shaped heating element. Alternatively, the heating element could be rectangular shaped to increase its surface contact area with the injected reductant and air mixture. In yet another alternative embodiment, an oxidizing catalytic
20 coating may be added to the evaporator unit, such as for example, a coating on the inner surface of the heating element housing and a catalytic cap at the point where the evaporated reductant and air mixture enters the exhaust gas manifold, to facilitate CO generation. The
25 catalytic coating may be a precious metal coating, preferably one containing Platinum or Palladium. Controller 12 controls the temperature of the heating element by providing a PWM signal of varying duty cycles. The duty cycle of the PWM control signal to the heating
30 element is determined from a prestored table based on operating conditions to achieve desired heating element temperature. Mixing unit 23 has a reductant inlet and an air inlet and an outlet 24 coupled to the evaporator unit 21 through which a mixture of reductant and air is

injected into the housing and subsequently comes into contact with the surface of the heating element 22. In an alternative embodiment (not shown), both air and reductant can be injected through a single input. The reductant can be supplied to the mixing unit 23 from the fuel tank or from a storage vessel. Air pump 25 supplies pressurized air to the mixing unit 23 thereby creating a mixture of reductant and air. Outlet 24 is configured to deliver the reductant and air mixture to more than one area on the surface of the heating element. Controller 12 can selectively enable and disable injection of the mixture to these areas depending on operating conditions, such as engine speed, load, exhaust gas temperature, etc. For example, when the amount of reductant required is high, such as at high load conditions, it may be necessary to enable delivery of the reductant and air mixture to more than one area on the surface of the heating element. Alternatively, outlet 24 may be configured to deliver the reductant and air mixture to a specific area on the surface of the heating element.

Figure 3B shows an alternate design for the heating element housing. As can be seen in the drawing, the heating element is surrounded by a delivery tube the inner diameter of which is wide enough to allow the heating element to be housed. The delivery tube has a narrow channel drilled into it, which serves as a passage for the air and reductant mixture. The air and reductant mixture is injected into the narrow channel and is rapidly vaporized by the heat provided by the enclosed heating element without coming into direct contact with its surface. In this embodiment, the durability of the heating element is further improved since the reductant and air mixture never comes into direct contact its surface. The delivery tube has one or more holes at its

tip through which the evaporated reductant and air mixture enters the exhaust gas manifold.

Figure 3C shows an alternative embodiment of the heating element housing shown in Figure 3B wherein a porous oxidizing catalytic plug, preferably one
5 containing Platinum or Palladium, is placed at the tip of the delivery tube to facilitate conversion of the vaporized hydrocarbons to carbon monoxide. Additionally, one or more ports may be drilled into the delivery tube
10 along its length and plugged up with porous oxidizing catalytic material to further facilitate conversion of hydrocarbons into carbon monoxide.

Therefore, according to the present invention, an improved reductant delivery system and method are
15 presented. Mixing reductant with air causes the reductant to be well distributed inside the reductant delivery system and thus speeds up the vaporization process. Also, system durability is improved by reducing lacquering and soot deposits through better distribution
20 of the reductant and faster evaporation process. The system performance is further improved through the addition of an oxidizing catalytic coating.

As will be appreciated by one of ordinary skill in the art, the routines described in Figures 4 and 5
25 below may represent one or more of any number of processing strategies such as event-driven, interrupt-driven, multi-tasking, multi-threading, and the like. As such, various steps or functions illustrated may be performed in the sequence illustrated, in parallel, or in
30 some cases omitted. Likewise, the order of processing is not necessarily required to achieve the objects, features and advantages of the invention, but is provided for ease of illustration and description. Although not explicitly illustrated, one of ordinary skill in the art will

recognize that one or more of the illustrated steps or functions may be repeatedly performed depending on the particular strategy being used.

Referring now to Figure 4, an exemplary routine for controlling the temperature of the heating element of the evaporator system in accordance with the present invention is described. First, in step 100, desired heating element temperature, T_{des} , is determined. This determination is based on what function the reductant evaporator system is performing, such as whether the mixture is to be evaporated or combusted. Next, the routine proceeds to step 200 wherein operating conditions known to have an effect on the heating element temperature, such as the exhaust gas temperature upstream of the ALNC, are evaluated. The exhaust gas temperature can be determined from a temperature sensor coupled in the exhaust gas manifold, or estimated based on parameters such as engine speed, load, engine temperature, ignition timing, etc. Next, in step 300, optimal duty cycle to achieve desired heating element temperature is determined from a prestored experimentally determined temperature map of the heating element based on operating conditions such as the exhaust gas temperature in this example. The routine then proceeds to step 400 wherein the duty cycle of the heating element control signal is adjusted to achieve desired heating element temperature. The routine then exits.

Therefore, by generating a map of the heating element temperature based on operating conditions, such as the exhaust gas temperature, or any parameter known to affect the temperature of the heated element, it is possible to dynamically control the temperature of the heated element to achieve optimal reductant and air mixture delivery while minimizing power consumption and

preventing overheating of the heating element. In other words, it is possible to take advantage of the heat provided by the exhaust gas passing through the reductant delivery system when controlling the temperature of the heating element. For example, higher exhaust gas temperature result in less power requirements, while lower exhaust gas temperatures result in higher power requirements. It is also possible to completely turn off power supply when the exhaust gas temperature is high enough to keep the heating element at desired temperature such as at high engine load conditions.

Referring now to Figure 5, an exemplary routine for controlling injection of a reductant into exhaust flow using a reductant vaporizer system as described in Figure 3A is presented. First, in step 500, the amount of NOx in the exhaust gas mixture entering the device, NOx_{fg} , is estimated based on engine operating conditions. These conditions may include engine speed, engine load, exhaust temperatures, exhaust gas aftertreatment device temperatures, injection timing, engine temperature, and any other parameter known to those skilled in the art to indicate the amount of NOx produced by the combustion process. Alternatively, a NOx sensor may be used to measure the amount of NOx in the exhaust gas mixture. Next, in step 600, the steady-state reductant injection amount, RA_{inj_1} , is calculated based on the following equation:

$$\frac{(RA_{fg} + RA_{inj_1})}{NOx_{fg}} = R_{des}$$

wherein RA_{fg} is the amount of reductant in the exhaust gas mixture entering the device, which can be determined based on engine operating conditions. This initial

reductant amount, RA_{inj_1} , is evaluated at steady state and yields a base reductant quantity to be injected for each engine speed and load point. The amount is calibrated to achieve a certain feedgas reductant to NOx ratio, R_{des} .

- 5 The ratio is typically obtained as a trade-off between NOx conversion and the fuel penalty due to reductant injection, and in this example is set at approximately 10. Next, in step 700, the steady-state base reductant injection amount, RA_{inj_1} , is modified to account for
- 10 engine operating conditions, such as engine coolant temperature, T_c , exhaust gas temperature, T_{eg} , EGR valve position, EGR_{pos} , start of injection, SOI , and other parameters:

$$15 \quad RA_{inj_2} = RA_{inj_1} \cdot f_1(T_c) \cdot f_2(T_{eg}) \cdot f_3(SOI) \cdot f_4(EGR_{pos})$$

The routine then proceeds to step 800 wherein the instantaneous change in the pedal position is computed as follows:

20

$$pps_diff(t) = \frac{(pps(t) - pps(t-1))}{T_s}$$

where T_s is the sampling rate, and $pps(t)$ denotes the pedal position at time t . Next, in step 900, a low pass filter

- 25 is applied to smooth out the noise:

$$pps_diff_lp(t) = (1 - k_f) \cdot pps_diff_lp(t-1) + k_f \cdot pps_diff(t-1)$$

where k_f controls the rate of filtering. The routine then

30 proceeds to step 1000 wherein the reductant amount is further modified to account for engine transient

behaviors as represented by the changes in the pedal position:

$$RA_{inj_3} = RA_{inj_2} \cdot f_s(pps_diff_lp)$$

5

where function f_s is shaped to allow overinjection of reductant during pedal position tip-in and underinjection of reductant during pedal position tip-out. In an alternative embodiment, instead of pedal position, engine speed or fuel demand sensor, or any other parameter known to those skilled in the art to provide a measure of engine transient behavior, may be used to obtain RA_{inj_3} .

Next, in step 1100, the desired temperature of the heating element is obtained as described with particular reference to Figure 4, thus achieving optimum temperature for reductant and air mixture evaporation. The routine then proceeds to step 1200 wherein the areas on the surface of the heating element to which a reductant and air mixture is injected are selected based on operating conditions. These areas are selected from a prestored map based on such parameters as the amount of reductant to be delivered, engine load, speed, exhaust gas temperature, catalyst temperature, throttle position, etc. For example, at high engine loads it may be desirable to inject the reductant and air mixture faster than at low engine loads, and delivery to more than one area will therefore be enabled. The routine then exits.

An example of f_s is shown with particular reference to Figure 6. Therefore, according to the present invention, in order to achieve more efficient exhaust aftertreatment device performance, the amount of reductant to be injected should be adjusted to account for increases and decreases in the amount of NOx in the exhaust gas

entering the device resulting from engine transient behavior. This can be accomplished by continuously monitoring engine parameters that are capable of providing a measure of engine transient behaviors, such
5 as a pedal position sensor, and continuously adjusting the amount of reductant to be injected as a function of filtered instantaneous changes in these parameters. Since NOx production typically increases at tip-in and decreases at tip-out, the result of such operation would
10 be to increase the base injected amount in the former case, and decrease the base injected amount in the latter case. Further, using a reductant vaporizer unit ensures fast system response, more efficient system operation, better emission control, and improved fuel economy.

15 This concludes the description of the invention. The reading of it by those skilled in the art would bring to mind many alterations and modifications without departing from the spirit and the scope of the invention. Accordingly, it is intended that the scope of
20 the invention is defined by the following claims: